Modeling induction machine winding faults for diagnosis

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Chapter 2

Modeling induction machine winding faults for diagnosis

In Electrical Machines Diagnosis

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2.1. Introduction

2.1.1. *Simulation model versus diagnostic model*

For a *simulation model* intended to validate a control reconfiguration in the presence of a winding fault situation, then the time available to the experimenter may vary from a few minutes to a few hours, depending on the desired level of precision. On the other hand, if the aim of the modeling is to on-line monitor an electrical drive by monitoring the parameters [----] of a *diagnostic model*, then the complexity of the model will become a prominent choice criterion.

In fact, monitoring parameters can be carried out by identification algorithms which differ depending on the model's structure and the criterion to be optimized [LJU 99, MEN 99]. In the typical case of a quadratic criterion based on the output error and the output of an unrefined model (in relation to the parameters), then classic optimization algorithms will use the criterion's (gradient and Hessian) limited development around the intermediate position [---] to generate the orientation and depth of research in the parameter space. However, experience shows that the analytical expression of the gradient and the Hessian is often needed to converge algorithms. Reducing the number of parameters is therefore an important objective in order to guarantee that the diagnostic model can be identified within the system's usage conditions, even if we can see that introducing *a priori* information may help us to solve this problem. On the other hand, the simplex algorithm [DAN 98] imposes no constraint on the model's analytical structure because only the system's simulated output is required. We can therefore completely envisage using more complex models, which are more like those suggested for a more accurate simulation of the machine, but at the cost of a considerably increased convergence time.

2.1.2. *Objectives*

The problematic issue of looking for a "good" diagnostic model is actually moving towards a more global problem of searching for a better compromise; the *diagnostic model-identification algorithm*. Another major aspect is the protocol for using the machine. Identifying a system requires a sufficiently thorough frequency spectrum of the input signal. For an electric car, the frequent phases of rapid acceleration and deceleration may potentially be enough to excite all the poles in the diagnostic model, which is actually no longer true for a fixed-speed or slow changing application.

From an operational point of view, the final choice will depend on the criticality of the diagnosis, in other words, the time between when the fault appears, its diagnosis (detection, location, characterization of fault severity) and the decision making process: is immediate shutdown required or could a control reconfiguration limit the effects of the fault whilst making it possible to obtain a sufficient electromagnetic torque until the next scheduled shutdown? In fact, with the latest speed varying devices, controlling currents by internal loops means that any minor malfunction will go unnoticed, without damaging the control's performance. For example, we will see that the controls are perfectly free from imbalances induced by a stator insulation fault, whether it displays a clear short-circuit on a few coils or a resistive contact of a few ohms between a high number of coils in the same phase. However, the fault current flowing in the coils mentioned here may be much higher than the

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rated current, inevitably leading to rapid over-heating in the conductors, and therefore, as a sort of chain reaction, to a generalized carbonization of the insulating wall.

Since the 1990s, French studies [CAS 04, LOR 93, MOR 99, SCH 99] which have focused on monitoring induction machines through parameter monitoring have shown that a short-circuit fault will not lead to any significant changes in the parameters of Park's two-phase model which is traditionally used in control. Consequently, one of the major stages in diagnosing electrical drives has been the development of diagnostic models which are fully adapted to describing winding faults, and can be identified in the machine's usage conditions. This chapter will deal with this subject.

2.1.3. *Methodology*

At a later stage, we will assume that the imbalances caused by winding faults will remain low enough so as to be able to continue to reason with the two-phase quantities [---] and [---], where [---] and [---] are the stator phase currents and voltages, and [---] is the Concordia matrix. Strictly speaking, this is no longer possible: in the case of a star connection, the line currents measured for control are also the phase currents, but the phase voltages for an unbalanced machine can no longer be deduced from the line voltages imposed by the inverter! On the other hand, for a triangle connection, the phase voltages are those imposed by the inverter (therefore known voltages), yet the phase currents are inaccessible[1]. This simplified assumption is highly important for the following section, because it makes it possible to use the simplified power of the Concordia and Park transforms for writing machine equations in the rotating field or rotor reference frame. This change in reference frame, in fact, makes it possible to relocate the spectrum of low frequency signals, thus simplifying the process of rendering the continuous state model discrete for numerical identification.

From a conceptual point of view, this hypothesis enables us to propose a two-mode model: a "common" mode and a "differential" mode. The common mode relates to the dynamic model of the induction machine with no fault, as used by the control (Park model). It explains the normal evolution of the machine's characteristics when in operation: these evolutions are caused by high variations in temperature, possible variations in magnetization, or even evolutions in iron losses. With regard to the differential mode, it aims to translate a malfunction in the machine, as its parameters ideally must only be sensitive to the faults being diagnosed.

This situation has proven to be favorable for introducing the *a priori* knowledge that we may have of the machine in order to facilitate the parameter estimation for the whole model. The Park model is typically parametricized by the stator resistance [---], the cyclic stator inductance [---], the rotor time constant [---], and the dispersion coefficient [---], where [---] represents the cyclic stator inductance and [---] represents the stator/rotor mutual inductance. In the presence of a control regulating the magnetizing flux amplitude, the inductive parameters [---] and [---] can be considered as constant. However, variations in temperature on the stator, and particularly the rotor, may lead to a large variation in the stator and rotor resistances, and therefore in [---] where [---] is the rotor resistance. This type of consideration means that we can significantly reduce the number of parameters in the model to be estimated on-line for diagnosis, and therefore also to impact the excitation protocol which is necessary to identify it.

2.1.4. *Chapter structure*

The first part of the chapter presents the hypotheses for study and the under-lying principles of modeling the machine in order to diagnose it. The concepts of rotating and stationary fields (in the electrotechnical sense of the term), as well as the equivalence between winding systems, will be dealt with in this first section. These are elementary yet fundamental conceptions for understanding winder fault modeling, whilst allowing us to introduce the notations which will appear in the chapter. The following section will go into detail on equation formulation and obtaining models in their basic form, suitable for detecting short-circuiting in coils in stator phase. In the third section, the approach is extended to modeling an imbalance in rotor winding. The last section will present the method and tools used to validate this diagnostic model. This relies on the results obtained from

[1] The matrix expressing the line current in relation to the phase currents is not reversible.

IREENA [SCH 99] and LAII [BAC 06, BAZ 08, MOR 99] who used similar power range induction machines (induction motors of 1.1 and 1.5 kW) but which used different excitation protocols and optimization algorithms.

2.2. Study framework and general methodology

2.2.1. *Working hypotheses*

Studying electrical rotating machines can be achieved by using rotating fields and introducing concepts of permeance and electromotive force (EMF), meaning, by means of inductances and matrix representation [DOE 09, TOL 04]. In this second case, the linearity hypothesis between the magnetic excitation [---] and the magnetic field [---] is vital because it allows for an extremely simplified notation of electrical equations which govern the machine’s dynamic operation. This simplified hypothesis is nonetheless especially justified in our study when we focus on a machine controlled at variable speeds, generally with a regulated magnetizing flux.

In addition, the manufacturers of induction machines ideally look to obtain a sinusoidal distribution in the current (and therefore in the magnetic excitation and flux) on the air-gap surface to limit oscillations in the electromagnetic torque. This second working hypothesis is not important because we can take into account the difference space harmonics, but at the price of a level of complexity which is too high in relation to the issues regarding our modeling procedure. In the following section, we will concentrate on modeling the squirrel cage induction machine in linear regime. In addition, we will also focus on the meaning of the first harmonic (meaning, fundamental harmonics), as much for the main rotating field as for the stationary field following a winding fault.

We will not be taking into account skin effects or capacitance effects, which are not relevant to the frequencies considered here in any way [MAK 97].

The final simplified hypothesis concerns modeling inter-coil short-circuits in the same phase through the “appearance” of a new short-circuited winding [---] which is evenly distributed in all the phase encoding whilst ignoring the reduced number of coils in the fault phase. A methodological justification of this is given in section 2.2.4. This hypothesis is probably the most debatable of all, but it is widely validated by experimental results. It will allow us, above all, to continue to exploit the concepts of rotating vectors when there is a stator or rotor winding fault, and thus to obtain an extremely simplified notation of electrical equations.

2.2.2. *Equivalence between winding systems*

2.2.2.1. *Stationary field and rotating field*

Using the hypotheses for study, the application of Ampere’s theory along the lines of electric flux (Figure 2.1a) shows that a stator winding [---] of [---] pole pairs with a current [---] running through it, creates a magnetic excitation in the air-gap at point [---], whose expression can be approached by:

[2.1]

where the physical angle [---] marks the field’s point of symmetry, [---] is the number of coils in series per phase, and the coefficient [---] characterizes the winding.

This is the expression for a stationary wave, hence the description of the stationary field which must not be confused with the statistical concept of stationarity. This field is usually represented by vector [---], with a norm which is proportional to the magnetic excitation amplitude of the air-gap in the direction of [---]:

[2.2]

with [---]. This vector is written in the reference frame [---] that we will call a *physical frame of reference* because it also corresponds to a physical section of the machine.

Figure 2.1. *Creation of a stationary field (a) and a rotating field (b)*

By taking note of the similarity between the expressions for current [---] and [---], it is interesting to represent this current in vector form in the same reference frame. If this seems natural, we must not forget that we are representing different magnitudes symbolically in the same place (meaning, in a section of the machine), because the magnetic excitation is intrinsically a spatial magnitude, whereas [---] is a purely temporal magnitude.

If a three-phase balanced stator winding (i.e. composed of three identical coils, distanced spatially from [---]) with [---] pole pairs which have a direct balanced sinusoidal system running through them with a current of [---], defined by:

[2.3]

then the expression for magnetic excitation in the air-gap becomes:

[2.4]

This is a progressive sinusoidal wave [---], which is periodic over one complete turn, rotating at an angular speed [---] in relation to the stator *physical frame of reference* (Figure 2.1b). We can combine this with the rotating vector [---]:

[2.5]

and so everything, then, happens as though the rotating excitation [---] were created by a rotating current [---]:

[2.6]

2.2.2.2. *Physical interpretation of Concordia's reference frame*

The previous result can be formalized using the Concordia orthonormal transform [---] where:

[2.7]

Let us consider any direct three-phase system [---] corresponding to a current, voltage or flux system. This system can be interpreted as the projection of a vector on the axes of its *natural* frame of reference [---] which has no particular physical meaning. The Concordia transform makes it possible to diagonalize the inductance matrix of a three-phase balanced winding. This corresponds to a transfer matrix from the *natural* reference frame towards *Concordia's* reference frame [---] where the system is written as:

[2.8]

When the system is balanced, the homopolar component [---] is zero, and the vector [---] is a vector from the plane [---], making an angle [---] with the axis [---]:

[2.9]

In the case of three-phase electrical machines, this transform has a very specific meaning, making the plane [---] coincide with a section of the machine. In fact, if the vector [---] of the stator phase currents has no physical meaning in its *natural* reference frame, then the vector [---] can, however, be interpreted as the vector representation of the dummy rotating current [---], previously defined by [2.6], at the origin of the rotating magnetic excitation[2].

Relations [2.9] and [2.5] prompt us to write the expression of peak amplitude of the magnetic excitation given by equation [2.5] in the following way:

[2.10]

meaning that everything will take place as though the magnetic excitation in the air-gap were created by a two-phase winding with [---] coils, with the two-phase balanced direct system with a current of [---] running through it:

[2.11]

2.2.2.3. *Voltage equations of real windings*

In fact, a three-phase system is only a special case of the [---]-phase system. We can show that any [---]-phase balanced winding system with [---] pole pairs and a q-phase balanced system with an angular frequency current [---] running through it, creates a progressive sinusoidal magnetic field in the air-gap, rotating at [---].Induction machine squirrel cages composed of [---] bars may thus be considered as a system of [---] elementary coils distanced at [---], where the [---]-th coil corresponds to two consecutive bars linked together by two sections of the ring, such as was defined in Figure 2.2.

Studying this type of rotor is, however, a special case, because rotor currents are likely to physically flow from one bar to any other bar, on the short-circuit rings.

[2]Note: a homopolar stator component [---] in the reference frame [---] has no physical existence in any way in an axial component [---] of the machine.

Figure 2.2. *Equivalent electrical diagram of a squirrel cage rotor*

Moreover, the number of bars is not necessarily a whole multiple of the number of pole pairs in the stator winding. A simple solution would consist of pointing out here, that the currents induced on the rotor tend to cancel out the effect of stator current which originally generated them (Lenz's law): the rotor currents try to flow within the bars so as to create a rotor field [---], going against the stator field [---]. Furthermore, the periodicity of the rotor field is imposed by the stator field, which is also [---]-periodical on one rotation. In permanent regime, with the hypothesis of a sinusoidal distribution of the field in the air-gap, the currents flowing in two consecutive rotor coils are dephased from [---] and make up a [---]-phase balanced direct current system. The generalized Concordia transform [---]:

[2.12]

thus enables us to express the rotor mesh currents [---], defined by Figure 2.2 according to the two-phase direct system [---] as follows:

[2.13]

The voltage equations for the balanced induction machine then become:

[2.14]

with:

[2.15]

[2.16]

[2.17]

where [---] is the rotor angular position, [---] is the self-inductivity of a stator phase, [---] is the mutual between two stator phases, [---] is the bar strength, [---] is the strength of a ring section linking two consecutive bars, and [---] is the maximum mutual between a stator phase and a rotor coil.

Let us call [---] the reluctance of the magnetic circuit taken by the main field lines, and [---] the reluctance of the circuit taken by the leakage lines. We can therefore express the stator winding inductances according to:

[2.18]

[2.19]

where the coefficient [---] of mutual inductance originates from the scalar product between the magnetic field [---] and the surface vector [---] when calculating the flux which is cut by the windings. We will see further on in this study the reason for expressing inductances through reluctances in order to determine short-circuiting winding parameters.

2.2.2.4. *Electrical parameters of equivalent two-phase windings*

By applying the Concordia transform [---] to the three-phase stator magnitudes, and [---] to the [---]-phase rotor magnitudes, then this will lead us to equations for the two-phase dummy electrical machine on the stator and rotor:

[2.20]

with:

[2.21]

[2.22]

[2.23]

[2.24]

[2.25]

[2.26]

The Concordia transform thus enables us to go from a *descriptive* modeling of stator and rotor windings to an equivalent, two-phase *dummy* modeling, as presented in Figure 2.3.

Figure 2.3. *Representation of a pole pair in the equivalent two-phase dummy machine on the stator and rotor*

As the equivalent stator windings are in phase quadrature, their mutual inductance is zero and the cyclic inductance [---] corresponds to their self-inductance, with:

[2.27]

However, with a hypothesis of sinusoidal distribution on the air-gap surface, we notice that the magnetic circuit taken by the principal field lines of a real coil, and the circuit taken by the principal field lines of an equivalent dummy coil are identical (Figure 2.4). We can deduce from this that the inductance [---] also corresponds to the principal inductance of the dummy two-phase stator winding with [---] coils and a resistance of [---].

In the same way, [---] corresponds to the self-inductance of the equivalent two-phase rotor winding, and [---] is the maximum mutual inductance between the dummy stator and rotor two-phase windings.

Figure 2.4. *Magnetic circuit of a real three-phase or equivalent two-phase winding*

2.2.3. *Equivalent two-phase machine with no fault*

2.2.3.1. *Equations in a non-specific reference frame*

The symbolic representation in Figure 2.3 involves *electrical* angles (for example, the electrical angle [---] referencing the motor), and *electrical pulsations*; it can therefore be applied to all machines, independently of the number of pole pairs. This is highly useful for understanding their operation, because it can manipulate rotating vectors in a plane which corresponds to a physical section of the machine, with the possibility of projecting them for control requirements (or identification) in any physical frame of reference [---]: the stator-fixed reference frame [---], the rotating reference frame linked to the rotor [---], or even the magnetizing field reference frame [---].

In the relations system [2.20], all the stator magnitudes have an angular frequency of [---], i.e. combined with vectors rotating at [---] in relation to the stator reference frame. All the rotor magnitudes at an angular frequency of [---] are combined with vectors rotating at [---] in relation to the rotor. To eradicate any ambiguity, we will henceforth specify the notation reference frame using an exponent. In any reference frame [---], referenced by the electrical angle [---] (Figure 2.3), then we obtain:

[2.28]

hence the equations for the machine connecting the vectors to same angular frequency. In other words, they all rotate at the same speed in relation to any notation reference frame [---]:

[2.29]

[2.30]

[2.31]

[2.32]

2.2.3.2. *State space representation*

For most industrial applications, the inertia in rotating components is high, and the rotor speed is a slow varying magnitude compared to the other electrical magnitudes in the machine. The electrical equations [2.29] to [2.32] enable us to obtain a representation of the following linear state which depends on four electrical parameters [---] and the ratio [---]:

[2.33]

with:

[2.34]

[2.35]

In fact, the system [---] is independent from [---]. It is enough to bring about the change in state variable:

[2.36]

in order to notice that the system's transmittance has vector [---] as an input, and the current vector [---] for the output is actually independent of the ratio [---]. This explains, from a theoretical point of view, the indetermination of the rotor's physical "realization". In fact, let us note [---] as the reluctance of the principal magnetic circuit, [---] and [---] the reluctances combined with the stator and rotor leakage inductances of the equivalent two-phase windings. We can therefore express the different inductances depending on the characteristics (dimensions, permeability) or the machine's magnetic circuit [SCH 99]:

[2.37]

By noting [---] as the resistance of a rotor coil, we will finally obtain expressions for [---] and [---] which only depend on the ratio [---] and the characteristics of the magnetic circuit:

[2.28]

The parameters [---] and [---] are clearly independent of the number of rotor coils. As the characteristics of the magnetic circuit and stator windings do not vary, then the machine's input/output behavior is therefore independent from the number of rotor coils, provided that the ratio [---] remains constant. To improve the rotor's solidity, machine designers have reduced the number of coils to the maximum limit by increasing their section: this is the squirrel cage rotor. To model this, choosing a value from the ratio [---] is a question of arbitrarily fixing a dummy number of coils (as well as their resistance) for both rotor phases in the equivalent two-phase machine. The most natural is to choose this ratio as being equal to the unit, such that:

[2.39]

2.2.4. *Consideration of a stator winding fault*

2.2.4.1. *Direct short-circuit or resistive contact*

The topology of the different short-circuits which may occur is varied, with more or less overlapping destructive consequences. As this was already dealt with in the introduction to this chapter, here we will focus more on the inter-coil contact in the same slot. This is a fault that can be compensated for by closed-loop control, whereas the current flowing in the respective coils may be very high.

In cases of direct contact, the short-circuit current amplitude is somewhat independent from the number of coils involved in the fault. A simple reasoning will allow us to show this: let us imagine a permanent sinusoidal regime, with a sufficiently low number of short-circuiting coils in a stator phase, so as not to interfere too much with the total rotating field [---]. By calling [---] the resistance of a stator coil, [---] the number of short-circuited coils and [---] the peak amplitude of the flux cut by a stator coil when there is a rotating field [---], then the expression of the short-circuit current [---] is given by:

[2.40]

with [---], and therefore:

[2.41]

Equation [2.41] shows that when there is a control maintaining a constant level of magnetization [---], then the current flowing through a few of the short-circuited stator coils is directly in proportion to the stator angular frequency, and remains virtually independent from the number of short-circuiting coils. In addition, when the resistive voltage drops, the product [---] corresponds to the amplitude of the stator phase voltage. For the experimental induction machine LS90 at [---] kW, the numerical application gives a short-circuit current amplitude of around [---] amperes on the nominal angular frequency, or rather 10 times more than the nominal current! Experiments can confirm this result: Figure 2.5 shows an experimental trial performed with a control on [---] in an open loop. The stator angular frequency is limited to [---] rad/s so as not to destroy the machine. We verify the proportionality between [---] and [---].

Figure 2.6 shows the evolution of the fault current amplitude [---] in relation to [---] for the angular frequency [---] rad/s. For low values of [---], we observe a slight difference between the experiment current and the synthetic current obtained using a multi-coil simulation model of a machine with a fault [SCH 99]. This is due to the resistance in the experimental connection performing a short-circuit.

Figure 2.5. *Evolution of current [---] in relation to speed*

Figure 2.6. *Amplitude evolution in current [---] in relation to the number of short-circuiting coils*

However, when there is an inter-coil resistive contact, the expression for the fault current flowing in the [---] coils becomes:

[2.42]

where [---] is the resistance of the inter-coil contact. The amplitude of the current flowing in the short-circuiting coils now depends on the ratio [---]. This current is the source of a stationary excitation [---] whose amplitude is given by equations [2.1] and [2.42]:

[2.43]

We notice that there is a multitude of combinations [---] which correspond to the same amplitude for the induced stationary field, and therefore also to the same changes in the machine’s input/output behavior. To fix such ideas, the numerical application shows that with the LS90 machine used for experimental trials, a direct short-circuit with [---] coils produces the same stationary excitation as [---] “short-circuited” coils through a contact resistance of [---], or even [---] coils for [---].

2.2.4.2. *Fault symmetrization*

The previous argument assumes an even distribution of the short-circuiting coils in all the phase slots, which is clearly not realistic. In reality, the coils brought into contact with each other are often physically located in two slots, coming back and forth between a single pole pair in any phase. Figure 2.7a shows an example of a short-circuit in two returning slots in the phase [---] of a machine with [---] pole pairs.

These coils are the cause of a stationary field which is not [---]-periodic over one turn of the air-gap. Nonetheless, we can show [SCH 99] that [---] short-circuiting coils located in a single pole pair will induce nearly the same electromotive forces in the different stator phases as [---] short-circuiting coils uniformly distributed in the [---] coils of [---] pole pairs in the machine, as is shown in Figure 2.7b.

The advantage of this fault symmetrization is to be able to continue to exploit the vector representation of different magnitudes (current, voltage, flux), as well as the symbolic representation of the machine which is equivalent to a pole pair, such as is shown in Figure 2.8. The electrical angle [---] references the axis of symmetry for the symmetrized coil [---].

Figure 2.7. *Symmetrization of real fault (a) through dummy coils distributed in all slots of the faulty phase (b)*

This working hypothesis may seem debatable, but it also enables us to remain within the framework for studying the machine in terms of first harmonics. It is nonetheless justified more when the fault is related to a low number of coils, in agreement with the realistic and industrially relevant objectives for diagnosing a drive with variable speeds.

2.3. Model of the machine with a stator insulation fault

2.3.1. *Electrical equations of the machine with a stator short-circuit*

2.3.1.1. *Electrical parameters of short-circuit winding*

In the following section, we will consider the uniform distribution of short-circuiting coils in the phase slots concerned, and we will ignore the reduced number of coils for the faulty phase. The expressions of inductance for the equivalent faulty dummy machine are those given by the equations in relation [2.37]:

[2.44]

[2.45]

where [---] and [---] correspond to the number of coils in the equivalent dummy two-phase windings.

Figure 2.8. *Symbolic representation of the machine with stator short-circuit*

Using the same reasoning which allowed us to obtain equations [2.18], [2.19] and [2.27], we can obtain the expression of the inductances for the new short-circuiting winding:

[2.46]

[2.47]

[2.48]

[2.49]

[2.50]

where [---].

2.3.1.2. *Vector relations in the stator reference frame*

By observing that [---], then the relations [2.46] to [2.50] allow us to write the scalar relations for voltage and flux for the short-circuiting winding:

[2.51]

[2.52]

As a current flowing in a winding is the source of a stationary field, it is indeed interesting to combine the scalar quantities [---] and [---] with the stationary vectors [---] and [---] whose expressions in the stator reference frame [---] are given by:

[2.53]

Relations [2.51] and [2.52] then become vector relations between stationary vectors in relation to the stator reference frame:

[2.54]

[2.55]

where the matrix [---] is defined by:

[2.56]

and the electrical vector equations for the two-phase dummy machine with a short-circuit finally become:

[2.57]

[2.58]

[2.59]

[2.60]

[2.61]

[2.62]

2.3.1.3. *Interpretation of the fault matrix* [---]

Through observing that the matrix [---] can also be written as:

[2.63]

We note that the stationary vector [---] simply corresponds to the projection of the rotating vector [---] on the axis of symmetry [---] of the short-circuiting coil [---]. Equations [2.59] and [2.62] finally correspond to the classic equations for the secondary winding of a transformer. Only the matrix [---] reminds us that the coupling between the primary and secondary winding is achieved here through the use of a rotating field.

2.3.2. *State model in any reference frame*

2.3.2.1. *Simplification of electrical equations*

If we choose [---] such as [---] as is proposed in relation [2.39], then [---] and equation [2.62] become:

[2.64]

As this is traditionally carried out for studying transformers or induction machines, we will realize variable changes:

[2.65]

[2.66]

meaning that we can introduce the flux and magnetizing current [---]:

[2.67]

In order to simplify the equations, we realize classic variable changes:

[2.68]

[2.69]

The voltage equations *brought back to the primary* are written in the stator reference frame [---]:

[2.70]

[2.71]

[2.72]

These equations correspond to the electrical diagram in Figure 2.9 which only differs from the electrical diagram of the equivalent two-phase machine (Park model) by the introduction of an extra dipole which dissipates the energy via the Joule effect in the short-circuiting coils with a stationary current running through it.

Figure 2.9. *Electrical diagram of the dummy fault machine*

2.3.2.2. *Final state space representation*

The previous vector equations can only be written simply in the stator reference frame [---] due to the matrix [---]. But the model notation in the reference frame of the rotating field or rotor simplifies this identification. Noting that the drop in resistive voltage [---] remains low before [---] for a wide operating range, then we can obtain the new electrical diagram in Figure 2.10 where the expression of short-circuit current becomes:

[2.73]

where [---] is the angle marking any reference notation [---].

We finally obtain a state space representation parameterized by the six classic parameters [---] or [---] for the ratio [---] and the angle marking the symmetrical axis of the faulty coil [---]:

[2.74]

We notice that the fault is similar to a simple error on the current measurement in Park's classic model. From a physical point of view, this current corresponds to the short-circuit current *brought back* to the primary. Its amplitude is different from the amplitude of current [---] in equations [2.41] and [2.42] by the transform ratio [---] of an equivalent dummy transformer with [---] coils in the primary and [---] coils in the secondary.

The point of this representation is to be able to express ourselves in an extremely simple manner in any reference frame, particularly in the rotor reference frame.

Figure 2.10. *Electrical diagram of the dummy faulty machine*

2.3.2.3. *Considering iron losses*

The consideration of iron losses in the equivalent electrical diagram for a transformer or an induction machine is traditionally achieved by introducing a dipole in a parallel circuit with the magnetizing inductance, whose expression of dissipated power can be approached by [---] [ROB 99]. We can therefore easily understand that during the parameter estimation phase, the optimization algorithm tends to attribute the fault dipole (Figure 2.10) to the iron losses. Integrating the iron losses in the diagnostic model thus greatly improves the quality of the diagnosis, particularly for a very low number of short-circuiting coils [SCH 99].

2.3.2.4. *Regarding the location of short-circuiting coils in the stator slots*

The angular position [---] of the back and forth slots in the fault can only be a finite known number with the values [---], where [---] is the number of stator slots. To reduce the number of parameters further, we can perform a spatial sweep by only estimating the five parameters [---]. Table 2.1 and Figure 2.11 show this process by representing the estimation evolutions for different values of [---]. The results are obtained using experiment recordings with an LS90 machine powered at [---] kW and controlled by a generic vector control and an excitation protocol, ensuring good convergence of optimization algorithms [SCH 99]. In Figure 2.11, each curve corresponds to a fault with [---] coils carried out in the phase [---] for [---] and in the phase [---] for [---].

On the one hand, we can verify that the estimated values of the four Park model parameters are actually independent from [--] (Table 2.1), and on the other hand that the estimation of [---] shows a maximum value in the angular direction corresponding to the axis of symmetry of the short-circuiting coils.

Figure 2.11. *Evolution in the estimation of [---] according to the angle for research [---] on the stationary field*

But above all, this Figure highlights that if the winding in each pole pair is distributed in a very low number of slots, or more generally, if the winding is concentric, then it is not useful to sweep [---] because we can be satisfied with the three values of [---] which correspond to the angular directions of the axes of symmetry for the three stator windings.

We also note that the curve obtained for a healthy machine is not flat. This phenomenon, observed for several machines, can very probably be explained by a fault caused by axial symmetry (the rotor axis of symmetry is shifted in relation to the stator axis of symmetry in the angular direction corresponding to the curve's maximum value). It shows the advantage in each case of performing an initial sweep in order to be able to carry out a diagnosis based on the analysis of the corrected ratio [---] where [---] corresponds to the estimated valued of [---] for the healthy machine. In fact, the curves clearly show that for a very low number of short-circuiting coils, not considering [---] can be extremely detrimental!

Table 2.1. *Evolution of the means and standard deviations (10 tries) according to [---] for a fault of [---] coils*

2.3.3. *Extension of the three-phase stator model*

We have just seen that a spatial sweep will allow us to dispense with estimating [---] and therefore to *a priori* simplify the cost of calculating the optimization phase. But this is, however, at the cost of repeating the sequence of operations for the [---] (or more) possible values of [---]. For some industrial applications[3], it may be interesting to use a diagnostic model which could simultaneously consider one fault in the three stator phases [BAC 06].

To do so it is simply enough to define three short-circuit windings [---] and [---] respectively, with a ratio of [---] and [---] in the angular directions [---] and [---]. This is a matter of putting 3 four-port networks, or quadripoles, in parallel [---], which explains the potential stationary field in each of the three angular directions (Figure 2.12). Each quadripole has a current [---] running through it, given by:

[2.75]

Figure 2.12. *Electrical model of the machine with faults in the three stator phases (in the rotor reference frame)*

2.3.4. *Model validation*

There are many methods of validating a diagnostic model. The first criterion to be verified is its ability to correctly simulate (i.e. explain) the fault which is to be monitored. For example, we can compare experimental currents with the currents simulated by the model for the same input (section 2.5.2), or at least in the same operating conditions. Thus, we propose to compare the spectrum of experimental and synthetic line currents for a machine powered by the network. The second criterion concerns the model's capacity to show a fault through the evolution of the parameters in its differential mode.

2.3.4.1. *Spectral analysis*

[3] In particular, those requiring the earliest possible fault detection.

The simulation of a drive requires that we take into account the electrical-mechanical equation of the machine:

[2.76]

where [---] is the speed of the driving shaft, [---] is the moment of inertia, [---] the electromagnetic torque, [---] is the set of resistive torques and [---] is the coefficient of viscous friction. The electromagnetic torque can be written in the two-phase reference frame connected to the rotor [GRE 97]:

[2.77]

By putting [2.77] into [2.76], we obtain the electromagnetic differential equation for the angular frequency [---]:

[2.78]

Then, by adding the dynamics of the rotor fluxes [---] and the stator currents [---] to the electromagnetic dynamics [---], then the drive may also be described by the non-linear state system:

[2.79]

with:

In simulations, the previous state system for a three-phase sinusoidal input current [---] must be solved. The solution is obtained by using the Runge-Kutta 4th order method with a sampling period of [---]. In experimentation, we can draw the power spectral density of the line currents for an induction machine of 1.1 kW, 4 poles (464 coils per phase), powered by the network and with a short-circuit of 58 coils in phases [---] and [---].

Figure 2.13 compares the power spectral densities obtained for the same fault in the same power supply conditions. The spectral analysis of the currents in Figure 2.13 reveals new components with frequencies of [---], which conform to our expectations [FIL 94, SCH 99].

Figure 2.13. *Power spectral density of line currents during a short-circuit on phases [---] and [---]*

2.3.4.2. *Evolution of fault parameter [---]*

We can also verify the model’s ability of finding the true value of the number of short-circuiting coils. Figure 2.14 shows the evolution (mean and standard deviation) of the parameter estimations of the diagnostic model [---] in relation to the number of short-circuiting coils for [---]. On the one hand, we can verify the relative independence of the [---] classic parameters of Park’s model, and the high level of correspondence between the estimated value of [---] and its theoretical value [---], even for a high number of short-circuiting coils[4].

[4]These results were obtained with a variation of model 2.74 which integrates the iron losses [SCH 99], for a series of 10 recordings.

Figure 2.14. *Evolution of the model's parameters according to the number of short-circuiting coils (mean and standard deviation)*

2.4. Generalization of the approach to the coupled modeling of stator and rotor faults

In the previous section, we modeled a short-circuit stator fault through a new short-circuited winding with [---] coils at the origin of a stationary magnetic field in relation to the stator, with an angular frequency [---]. The main simplified hypothesis consisted of ignoring the reduced number of corresponding coils in the faulty phase, as well as the effect of the homopolar stator current in the line current calculations. The idea is to extend this approach to a rotor fault study. This may be a bar break, or more generally a rotor imbalance related to the progressively increased size of a crack during frequent temperature changes.

The increase strength of a bar [---] limits the flow of the induced current [---] defined by Figure 2.2, and it locally deforms the magnetic rotor field [---]. However, we can consider the unbalanced system [---] of the mesh currents as the superposition of a balanced system with currents [---] and a system of currents [---] flowing in the opposite direction in the meshes affected by the fault. This means that everything takes place as though the rotor field were the result of the superposition of field [---] produced by a faultless rotor, and of the field [---] which is stationary in relation to the rotor, produced by a dummy short-circuiting winding [---] whose axis of symmetry coincides with the axis of symmetry of field [---] (Figure 2.15).

Of course, this is pure abstraction which nevertheless stems from a rather classic approach from electromagnetism. In addition, with the angular frequency of the rotor currents being [---], then the stationary field [---] oscillates at a frequency of [---] in relation to the rotor. Moreover, if we want the dynamic of the fault currents [---] to be identical to the dynamic of the currents [---], then a simple solution would consist of considering (by analogy with the previous approach) that the coils in the dummy winding [---] have the same electrical characteristics (resistance and inductance) as those characteristics in the two equivalent dummy rotor phases.

Figure 2.15. *Symbolic diagram of the machine with rotor unbalance*

2.4.1. *Electrical equations in the presence of rotor imbalance*

Let us now consider our rotor as the superposition of a balanced two-phase system and an additional short-circuiting winding with [---] coils, where [---] characterizes the importance of the fault, and where [---] is the number of coils in the equivalent dummy rotor phases. The equations of voltage and flux can be written in the rotor reference frame:

[2.80]

[2.81]

where the angle [---] marks the axis of symmetry of the stationary field [---] in relation to axis [---] (Figure 2.15).

In addition, we recall here that it is indeed possible to choose the dummy number of coils [---] from the equivalent rotor winding such as [---]. By combining the scalar quantities [---] and [---] to the stationary vectors:

and combining relations [2.80] and [2.81] to the classic equations of the induction machine rotor, then we can finally obtain the system of equations for the machine in the presence of rotor unbalance:

[2.82]

[2.83]

[2.84]

[2.85]

[2.86]

[2.87]

with:

[2.88]

2.4.1.1. *Equivalent electrical diagram*

In the rest of the chapter, all the vectors will be written in the rotor reference frame. The change in the variable [---] allows us to rewrite [2.83] and [2.86] in the following way:

[2.89]

[2.90]

These correspond to the electrical diagram in Figure 2.16. We notice that the coil [---] which represents the fault is brought back to a simple resistive dipole [---] which is put in a parallel circuit with the magnetizing inductance and the rotor resistance.

Figure 2.16. *Modeling rotor imbalance*

To simplify the formulation of state system equations further, then it would be well-advised to add up the impedances of the rotor [---] and the fault [---] in an equivalent impedance matrix [---] by putting them in a parallel circuit [BAC 06]:

[2.91]

where the matrix [---] is the identity matrix of dimension 2.

By remembering that [---], then we can easily obtain the expression for the impedance matrix [---]:

[2.92]

Figure 2.17 shows the equivalent diagram for the inductance machine with a rotor fault in the dynamic regime in the rotor's reference frame. When the machine is healthy (therefore [---]), then we find again Park's classic model. For a non-zero value of [---], then the fault matrix [---] introduces an imbalance as well as coupling terms on the rotor's two axes [---] and [---].

Figure 2.17. *Model of machine with rotor fault*

2.4.1.2. *Validation in stationary regime*

The numerical integration of the model is performed in the same conditions as those described in section 2.3.4.1. The experimental machine is equipped with a rotor with two bars divided into sections [BAC 06]. Figures 2.18 and 2.19 show that in experiments just as much as in simulations, we find harmonic components with [---] signatures of a rotor fault [INN 94].

Figure 2.18. *Spectral analysis of line currents during a bar break: synthetic signals*

Figure 2.19. *Spectral analysis of line currents during a bar break: experimental signals*

2.4.2. *Generalized model of the machine with stator and rotor faults*

We previously saw how a winding fault results in the appearance of a stationary field (in relation to the winding involved), with the main consequences being abnormal overheating in the concerned zone through the Joule effect, and the appearance of new spectral components in the machine's different magnitudes (currents, voltages, torque, etc.). Whether it is a design problem on the rotor (impurity or static eccentricity), or a failing weld join between a bar and its short-circuit ring, or even advanced degradation in the stator insulation, any imbalance leads to accelerated ageing in the machine's different components through a chain effect. It might be interesting to perform a simultaneous diagnosis of imbalances on the stator and rotor.

As these have different signatures, we can superimpose the two models obtained previously. In the following, we will propose to study the global model of stator/rotor faults (Figure 2.20) which involves modeling the healthy machine (Park's model), modeling the contact between stator coils in the same phase and an imbalance in the rotor resistances through the fault matrices [---] and [---].

To simplify the notation, we will no longer indicate the reference frame (specified by the exponent). The 4th order state space representation of the induction machine with a winding fault (where the speed [---] is a measured pseudo-input) relating to the electrical diagram 2.20 is in the following form:

[2.93]

with:

Figure 2.20. *Model of stator-rotor faults*

2.5. Methodology for monitoring the induction machine

The diagnosis strategy consists of monitoring the parameters of the differential mode (fault parameters). Of course, monitoring parameters must also take into account normal and predictable variations in the parameters of the common mode which are exclusively due to the operating conditions (temperature, the machine's magnetic state, etc.).

2.5.1. *Parameter estimation for induction machine diagnosis*

The theoretical concepts of identification using output error are widely discussed in literature [LJU 99, RIC 98, TRI 01]. Also in this section we will endeavor to present its application in the special case of diagnosing induction machines.

2.5.1.1. *Identification through output error*

The generally implemented method, commonly known as the model method, applied to estimating the parameters of the induction machine can be symbolized by Figure 2.21. In this case, the approach used is a "direct approach" which processes data gathered in a closed loop in the same way as for an open loop. With the presence of looping at a speed of [---], and currents[5], then [---] is therefore not taken into account and is not supposed to alter the parametric identification. In fact, with this looping, we find an input with a voltage input [---] which is correlated with the output disturbance [---] (and also that for the speed measurement): the estimation is, therefore, asymptotically biased [BAZ 08, LJU 99]. In our case, we circumvent this difference by paying particular attention to the measurement in order make the signal : noise ratio the highest possible. However, there are algorithms for identification through output error intended for the closed loop, and they will be demonstrated in the following chapter. They allow a perfect rejection of the bias, but at the cost of a more complex implementation.

Let us consider the monitoring model which describes the superposition of the common mode [---] characterized by the vector parameters [---], of the differential stator [---] and rotor [---] mode. In this model, [---] summarizes the expertise of the machine user, in other words, his/her knowledge of the electrical parameters [---] and their variance [---], as well as noise affecting the output, i.e. their variance [---]. This nominal model is only sensitive to predictable parametric variations. This is the contrary to the error models [---] and [---] which constitute a true fault signature, both in terms of their structure as well as their parameters [---] and [---]. Within the framework of diagnosing simultaneous stator/rotor faults in the machine, we therefore define the vector of the extended parameters [---] to be estimated as:

[2.94]

The strategy of induction machine diagnosis consists of carrying out many estimations of vector [---]. The mean of the parametric estimations [---] indicates the number of coils short-circuiting on each of the three phases. The parameter [---] enables us to evaluate the magnitude of a potential rotor fault.

---

[5] On the speed varying devices, current looping operates by internal regulation loops.

We define the estimation error vector (identification residual written [---] between the measured [---] and simulated [---] currents) by:

[2.95]

The optimum value of [---] is obtained by minimizing the multivariable quadratic criterion according to:

[2.96]

Figure 2.21. *Principle of the output error method applied to the induction machine*

where [---] and [---] are sampled measurements at period [---] (with [---] varying from 1 to K points). The estimated currents [---] and [---] represent the model simulation based on an estimation of the parameter vector [---].

As the output [---] is not linear in [---], then minimizing this criterion can be achieved by a non-linear programming method [RIC 98]. The optimum value of the parameter vector written [---] is obtained by an iterative optimization algorithm. The Marquardt algorithm [MAR 63] offers a good compromise between robustness and convergence speed. The parameters to be estimated are updated in the following way:

[2.97]

Optimization management is achieved by calculating the gradient and the Hessian by using functions of parametric sensitivity:

[---]: gradient;

[---]: Hessian approximation;

[---]: control parameters;

[---]: functions of sensitivity in relation to the output [---];

[---]: functions of sensitivity in relation to the output [---].

This algorithm, thanks to the control over parameter [---] during the research, enables us to evolve between a gradient technique which is far from being the optimum (thus [---]) and a Newton technique (when [---]) which makes it possible to accelerate the convergence around the optimum.

The differential system enabling the simulation of sensitivity functions can be directly deduced from a state space representation of the induction machine (equation [2.93]):

[2.98]

where [---] represents the output sensitivity matrix in relation to the parameters, and [---] represents the sensitivity matrix in relation to the state.

2.5.1.2. *A priori information and diagnosis*

Introducing *a priori* information into a parametric estimation process was originally intended for problems of sensitization. In fact, the identifier using the aforementioned algorithm is often faced with anomalies, such as obtaining parameters which are far removed from physical reality, or even completely absurd parameters such as negative resistances or inductances. This is partly due to problems of sensitization or identifiability which can be solved by a more persistent excitation when the process allows it. Another method consists of imposing realistic constraints on the parametric space by introducing the user's expertise. In fact, when we have available knowledge on the parameters which are to be estimated, then to the experimental criterion [---] which is weighted by the noise variance [---], we may combine a quadratic term which represents this information (parameter values written [---] weighted by their variance [---]) according to the following formula [MOR 99]:

[2.99]

When the *a priori* information is certain and accurate, this methodology may prove to be very useful and ensures good convergence, particularly for processes which are sensitive to the choice of excitation, as for electrical drives [TRI 03].

In the diagnostic framework, only the nominal model [---] must include the *a priori* information, summarized by [---]. As there is no available knowledge on these faults, then the *a priori* values of the parameters for the differential modes [---] and [---] are zero, whereas their variances are infinite (or extremely high), such as:

In practice, variances in the electrical parameters [---] are obtained either through physical knowledge (manufacturer's data and/or elementary experiment), or by preliminary estimates. In each case, these variances must tolerate predictable parametric estimations (for instance, a change in the operating conditions). In addition, no constraint is imposed on the fault parameters because their estimates can only provide experimental data via criterion [---].

2.5.2. *Experimental validation of the monitoring strategy*

2.5.2.1. *Experimental system*

In practice, the academic testing stand which makes it possible to test all monitoring methods is shown in Figure 2.22. The machine is speed controlled by a vector control speed varying device. A dynamic load producing a resistive torque is positioned on the machine's shaft, followed by a position/speed sensor (incremental encoder). The three-phase currents and voltages are measured and conditioned by anti-folding filters before acquisition.

Parametric identification algorithms require, in order to converge, persistent excitation which sufficiently sensitizes all the modes in the system. As the induction machine is speed controlled, then the simplest and most natural excitation consists of interfering with the reference speed by adding a pseudo random binary sequence (PRBS) to it. However, this excitation remains problematic for applications with constant speed. So as not to restrict ourselves to a particular application, we may define another excitation protocol under constant speed obtained by adding sinusoidal signals to the inverter's reference voltage [BAC 05]. The results will be presented for both methods in the following section.

Figure 2.22. *Testing stand for identification and control of the induction machine*

In order to realize the faults experimentally, the machine has been completely rewound in order to access the intermediate tap points. These tap points are distributed over phases [---] and [---] with the aim being able to short circuit a number of coils in a quasi-geometric progression. Thus, the terminals which are accessible from the exterior correspond to 18 coils (3.88%), 29 coils (6.25%), 58 coils (12.5%) and 116 coils (25%). There are different interchangeable rotors available on the testing stand, including a healthy rotor with 28 slots and two faulty rotors (one and two broken bars). As the technique shown previously enables us to pinpoint predictable parametric fault variations (due to overheating, for instance), then we may imagine a test at a high operating temperature (50° instead of 35°). To do so, a temperature gauge is inserted between the motor and the stator windings.

2.5.2.2. *Implementation*

A priori information is gathered using an average of 10 preliminary recordings for different temperatures in order to envisage all the situations likely to vary the parameters (normal change in the machine's state). For all the identification tests, we used:

[---]

The noise variance is equal to: [---]

It is important to note here that the initial angle [---] results from the first sweep in order to detect a peak in the parameter [---].

It may be interesting to analyze the behavior of the model during the simultaneous stator and rotor faults. Thus, we proceed with a series of tests using short-circuits on several stator phases and bar breaks. The following tests were carried out:

1) healthy machine,

2) short-circuit of 18 coils on phase [---] and one broken bar,

3) short-circuit of 18 coils on phase [---] and 58 coils on phase [---], and two broken bars,

4) high heat test (50°): short-circuit of 58 coils on phase [---] and 29 coils on phase [---], two broken bars.

Table 2.2 summarizes the results from the parametric estimation for the set of tests.

Table 2.2. *Results from parametric estimation*

For the coil short-circuits on the stator, the results achieved show the similarity between the estimated parameters and the real parameters of the fault (a maximum error of five coils for excitation under speed, and two coils for excitation under voltage). The indicator [---] denotes the rotor's fault rate: the higher the number of broken bars, then the higher this parameter will be, and vice versa. Thus, the parametric identification algorithm using *a priori* information is robust when faced with simultaneous stator/rotor faults. This indicates that the fault quadripoles are not competing for an explanation of the unbalance in the machine.

In addition, we may notice that on the last test, only the resistances [---] and [---] were affected by the change in temperature. Figures 2.23 and 2.24 show precisely how the rise in temperature does not affect the differential mode.

Figure 2.23. *Parameter evolution for a high heat test with faults (test 4) – resistance and inductance*

Still for the same test, Figures 2.25 and 2.26 compare the real current and the estimated current on Park's axis [---]. We notice that the error of estimation [---] is insignificant for both modes of excitation, which allows us to draw a conclusion with regard to the model's abilty to interpret simultaneous stator/rotor faults.

Figure 2.24. *Parameter evolution for a high heat test (test 4) – number of short-circuiting coils*

Figure 2.25. *Comparison of currents [---] and [---] for excitation under speed*

Figure 2.26. *Comparison of currents [---] and [---] for excitation under current*

2.6. Conclusion

An advanced degradation in the stator insulator will result, electrically, in a resistive contact between the winding coils, depending on different topologies, which can be very varied. In some cases, through a chain effect, the contact may lead to a somewhat immediate destruction of the winding. In other cases, the drive controls at variable speeds using current loops may partly compensate for its effects, by immediately maintaining the drive's dynamic performances. This is a typical example of the direct or resistive short-circuit between a few consecutive coils in the same phase. Implementing a maintenance strategy or reconfiguring the control in damaged mode require a diagnosis of the short-circuit current amplitude, as it is this (via the Joule effect) which will accelerate the degradation process. This is the entire problem with diagnostic oriented modeling of induction machines, as presented in this chapter.

The approach used for modeling is based on a fundamental hypothesis of superimposing two operating modes: a common mode combined with the rotating field, created by the machine's windings with no fault, and a differential mode combined with a stationary field in relation to the rotor, in the case of a rotor imbalance. An important characteristic of the diagnostic model is that it remains extremely close to the model which is classically used to control at variable speeds, with, notably, the possibility of notation within the different reference frames (stator, rotor, or rotating field).

This characteristic is essential for converging estimation algorithms well. In this chapter, we have proposed and validated the diagnosis of the machine through parametric identification in a more global, comprehensive approach. We have shown that parametric monitoring of the diagnosis model not only makes it possible to locate a fault in the stator or rotor winding, but also to determine its severity.

Identifying the parameters of the inductance machine has been practiced for a long time in a quasi open loop approach, even in the presence of a speed regulator which ensures its drive. However, by working on the machine's control voltages and on the line current measurements, we forget that the drive is ensured by looping the outputs under current and speed. Fundamentally, this type of identification causes theoretical problems due to the stochastic interferences that we find on the control variable via the regulation loop, which makes the estimation asymptotically biased. This specific problem will be the main object for study in the next chapter, through a general and realistic methodology of closed-loop identification applied to induction machines.

2.6. Bibliography

[BAC 05] BACHIR S., TNANI S., CHANPENOIS G., GAUBERT J. P., "Stator faults diagnosis in induction machines under fixed speed", *European Conference on Power Electronics and Applications, EPE, Dresden, Germany, September 2005.*

[BAC 06] BACHIR S., TNANI S., TRIGEASSOU J.-C., CHANPENOIS G., "Diagnosis by parameter estimation of stator and rotor faults occurring in induction machines", *IEEE Transactions on Industrial Electronics*, n°53(3), p. 963-973, 2006.

[BAZ 08] BEN AMEUR BAZINE I., Identification en boucle fermée de la machine asynchrone: application à la détection de défaut, PhD Thesis, University of Poitiers, Ecole Supérieur d'Ingénieurs de Poitiers/Ecole Nationale d'Ingénieurs de Tunis, 2008.

[CAS 04] CASIMIR R. *et al.*, «Comparison of modelling methods and of diagnostic of asynchronous motor in case of defects », *9th IEEE International Power Electronics Congress, CIEP*, Celaya, GTO, Mexico, October 2004.

[DAN 98] DANTZIG G. B., *Linear programming and extensions*, Princeton University Press, 1998.

[DOE 09] LE DOEUFF R., ZAÏM E.H., *Machine électriques tournantes - de la modélisation matricielle à la mise en œuvre*, Hermès, Paris, 2009.

[FIL 94] FILLIPPITTI F., FRANCESHINI G., TASSONI C., VAS P., "Broken bar detection in induction machine: comparison between current spectrum approach and parameter estimation approach", *IAS'94*, New York, p. 94-102, 1994.

[GRE 97] GRELLET G., CLERC G., *Actionneurs électriques. Principes, modèles et commande*, Eyrolles, Paris, 1997.

[INN 94] INNES A. G., LANGMAN R. A., "The detection of broken bars in variable speed induction motors drives", *ICEM'94*, December 1994.

[LJU 99] LJUNG L., *System Identification: Theory for the User*, Prentice Hall, Upper Saddle River, 1999.

[LOR 93] LORON L., "Application of the extended Kalman filter to parameter estimation of induction motors", *EPE'93*, vol. 05, Brighton, p. 85-90, September 1993.

[MAK 97] MAKKI A., AH-JACO A., YAHOUI H., GRELLET G., "Modelling of capacitor single-phase asynchronous motor under stator and rotor winding faults", *IEEE International SDEMPED'97*, Carry-le-Rouet, France, p. 191-197, September 1997.

[MAR 63] MARQUARDT D. W., "An algorithm for least-squares estimation of non-linear parameters", *Soc. Indust. Appl. Math*, vol. 11(2), p. 431-441, 1963.

[MEN 99] MENSLER M., Analyse et étude comparative de méthodes d'identification des systèmes à représentation continue. Développement d'une boîte à outil logicielle, PhD Thesis, University of Nancy I, 1999.

[MOR 99] MOREAU S., Contribution à la modélisation et à l'estimation paramétrique des machines électriques à courant alternatif : Application au diagnostic, PhD Thesis, University of Poitiers, Ecole Supérieur d'Ingénieurs de Poitiers, 1999.

[RIC 98] RICHALET J., *Pratique de l'identification*, 2nd edition, Hermès, Paris, 1998.

[ROB 99] ROBERT P., *Traité de l'électricité vol. 2 : Matériaux de l'électrotechnique*, Presses polytechniques et universitaires romandes, 1999.

[SCH 99] SCHAEFFER E., Diagnostic des machines asynchrones: modèles et outils paramètriques dédiés à la simulation et à la détection de défauts, PhD Thesis, University of Nantes, Ecole Centrale de Nantes, 1999.

[TOL 04] TOLIYAT H. A., KLIMAN G. B., *Handbook of Electrical Motors*, Marcel Dekker, New York, 2004.

[TRI 01] TRIGEASSOU J. C., POINOT T., « Identification des systèmes à représentation continue – Application à l'estimation de paramètres physiques », in Landau L.D. and Besançon-Voda A. (ed.), *Identification des systèmes*, Hermès, Paris, 2001.

[TRI 03] TRIGEASSOU J. C., POINOT T., BACHIR S., « Estimation paramétrique pour la connaissance et le diagnostic des machines électriques » *de commandes des machines électriques*, Hermès, Paris, 2003.